Measurement Of Direct Photon Higher Order Azimuthal Anisotropy

In $\sqrt{s_{NN}}=200$GeV Au+Au Collisions at RHIC-PHENIX

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Pre-defense Session
Jan. 23th 2015
Outline

✓ Introduction
  • Direct photon
  • Motivation

✓ Analysis
  • PHENIX detector
  • Analysis method

✓ Results and Discussion
  • Neutral pion $v_n$
  • Direct photon $v_n$
  • The probability of resolving photon puzzle

✓ Summary

2015/1/23
Introduction
Quark-Gluon Plasma at heavy ion collision

Quarks and gluons are predicted to move freely in the state of extremely high temperature and dense matter.

QGP has been created at high energy heavy ion collision.
- RHIC at BNL
- LHC at CERN

Lattice-QCD calculation predicts
\[ \varepsilon \approx 1 \text{GeV/fm}^3 \]
\[ T \approx 170 \text{MeV} \]
Direct photon analysis
All photons except for those originating from hadron decays.
- emitted during all stages of the collisions
- don’t interact with the medium
The excess of direct photon

The excess of direct photon has been measured via several methods.

The virtual photon method and external conversion photon method are sensitive to low $p_T$ region.

Less than 4 GeV/c, direct photons are included by 20% in inclusive photon.

$$R_\gamma = \frac{N_{inc.}}{N_{dec.}}$$

P.R.L. 94, 232301
arXiv:1405.3940
P.R.L. 104, 132301
Direct photon $p_T$ spectra

The $p_T$ spectra in Au+Au collision is enhanced compared with that in p+p collision scaled by the number of binary collisions less than 4 GeV/c.

The excess of $p_T$ spectra is fitted and effective temperature is extracted. (Freeze out temperature $\approx$ 100MeV)

Photons in low $p_T$ are mainly radiated from very hot medium at early time of collisions.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Effective temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% - 20%</td>
<td>239 ± 25 ± 7 (MeV)</td>
</tr>
<tr>
<td>20% - 40%</td>
<td>260 ± 33 ± 8 (MeV)</td>
</tr>
<tr>
<td>40% - 60%</td>
<td>225 ± 28 ± 6 (MeV)</td>
</tr>
</tbody>
</table>
Azimuthal anisotropy (Elliptic flow)

\[ v_2 = \langle \cos \left\{ 2(\phi - \Psi_{R.P.}) \right\} \rangle \]

charged particle \( d\phi \) distribution

- anisotropic pressure gradient in participant zone (Initial state)
- QGP expansion (hydrodynamic motion, \( \eta/s \))
  \( (\eta \) is shear viscosity and \( s \) is entropy density)
- hadron production mechanism (coalescence)

(1) : **Initial geometry** is converted into final azimuthal anisotropy
(2) : (expected to be) sensitive to \( \eta/s \).

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The measurement of photon azimuthal anisotropy is a powerful probe to identify the photon sources.
High $p_T$: very small $v_2$

It is consistent with expectation that photons produced in the initial hard scattering are dominant.

Low $p_T$: Comparable to hadron $v_2$ at around 2 GeV/c
Direct photon puzzle

Thermal radiation photons are dominant in low $p_T$ region.

Elliptic flow:
Photon should have small $v_2$, since it includes one from early stage having small $v_2$,
-> Photons are dominantly emitted at late stage.

$p_T$ spectra:
Emitted from very hot medium ($T_{\text{eff}} \approx 240\text{MeV}$).
-> Photons are dominantly emitted at early stage.

There is a discrepancy, and it is called “direct photon puzzle”.
There is no models to explain both observables simultaneously.
Third order azimuthal anisotropy (v₃)

The higher order flow is expected to constrain the initial geometry calculating model and η/s of QGP.

v₃ is originating from fluctuation of the shape of participants.
Why direct photon $v_3$ is measured?

Radial flow effect (blue shift effect) :
It makes effective temperature higher than true temperature.
Photons from late state are dominant.
$v_2 > 0 : v_3 > 0$

Large magnetic field :
Direction of magnetic field is strongly related with $\Psi_2$(R.P.) but not with $\Psi_3$.
$v_2 > 0 : v_3 \approx 0$

$v_3$ measurement could provide additional constraint on photon production mechanism.
My activity

2012 (D1): Data taking shift and Detector expert & TOF calibration

- Poster
- Talk
- Poster
- QM 2012
- Talk
- ATHIC 2012
- Talk
- JPS spring

Identified particle azimuthal anisotropy

2013 (D2): Data taking shift and Detector expert & TOF calibration

- Talk
- JPS fall
- Talk
- JPS spring

Neutral pion and direct photon azimuthal anisotropy

2014 (D3): Data taking shift and Detector expert

- Talk
- QM 2014
- Talk
- HIC HIP
- Talk
- ATHIC 2014
- Talk
- WPCF 2014

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Analysis
Reaction Plane detector (RxNP), MPC, BBC are used for measuring Event Plane.
Photons and $\pi^0$ are detected by EMCal in CNT.

$$\nu_n = \left\langle \cos \left\{ n \left( \phi - \Psi_n \right) \right\} \right\rangle$$
Centrality determination

Centrality:
The size of participant zone is classified by multiplicity in BBC.

Beam-Beam Counter (BBC):
Measures charged particles.
Event plane and resolution

Event plane is determined for each harmonic “n”.

\[ \Psi_n = \frac{1}{n} \tan^{-1} \left( \frac{\sum w_i \sin n\phi_i}{\sum w_i \cos n\phi_i} \right) \]

\[ \text{Res}(\Psi_n) = \langle \cos \left\{ n(\Psi_n^{\text{true}} - \Psi_n^{\text{obs.}}) \right\} \rangle \]

\[ \nu_n^{\text{true}} = \nu_n^{\text{obs.}} / \text{Res}(\Psi_n) \]

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Photon reconstruction

**Pad chamber**: space point of charged particle track

**Electromagnetic calorimeter (EMCal)**

Photons are reconstructed

- Energy threshold: $E > 0.2\text{GeV}$
- Shower shape: $\chi^2 < 3$
- Charged particle rejection at PC3: $\sqrt{(d^2+\left(r_T\sin(d\phi)\right)^2) > 6.5$

$\pi^0 (\rightarrow \gamma+\gamma)$ reconstruction

- Asymmetry cut: $|E_1 - E_2|/(E_1 + E_2) < 0.8$
- Photons are detected in same sector
- Invariant mass of $\gamma+\gamma$

$$Mass = \sqrt{2E_1 E_2 (1 - \cos \theta)}$$

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Inclusive photon $v_n$ measurement

The method of extracting $v_n$
1. $v_n = \langle \cos\{n(\phi-\Psi_n)\} \rangle$
2. $dN/d\phi$ is fitted by $N_0\{1+2v_n\cos\{n(\phi-\Psi_n)\}\}$

Systematic uncertainty
- Photon selection
- $v_n$ measuring method
- Event plane determination

Count

$20-30\%$
$2.0<p_T<2.5(\text{GeV/c})$

$N_0\{2v_n\cos\{n(\phi-\Psi_n)\}\}$

Systematic uncertainty
- Photon selection
- $v_n$ measuring method
- Event plane determination

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PreDefence (M.Sanshiro)
Neutral pion $\nu_n$ measurement

The number of $\pi^0$ is counted with respect to the event plane. The azimuthal distribution is fitted by the equation.

$$N_0(1 + 2\nu_n \cos \{n(\phi - \Psi_n)\})$$

Systematic uncertainty
- Photon selection
- $\pi^0$ selection
- Event plane determination

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Hadronic decay photon

It is impossible to identify photons originating from hadron decay experimentally.

Decay photon $p_T$ spectra and $v_n$ should be simulated by Monte-Carlo simulation.

<table>
<thead>
<tr>
<th>meson</th>
<th>invariant mass(MeV/c²)</th>
<th>decay mode</th>
<th>branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>134.98</td>
<td>$2\gamma$</td>
<td>$(98.823 \pm 0.034)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e^+e^-\gamma$</td>
<td>$(1.174 \pm 0.035)$ %</td>
</tr>
<tr>
<td>$\eta$</td>
<td>547.86</td>
<td>$2\gamma$</td>
<td>$(39.41 \pm 0.20)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$(4.22 \pm 0.08)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$e^+e^-\gamma$</td>
<td>$(6.9 \pm 0.4) \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^02\gamma$</td>
<td>$(2.7 \pm 0.5) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>782.65</td>
<td>$\pi^0\gamma$</td>
<td>$(8.28 \pm 0.28)$ %</td>
</tr>
<tr>
<td>$\rho$</td>
<td>775.26</td>
<td>$\pi^+\pi^-\gamma$</td>
<td>$(9.9 \pm 1.6) \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi^0\gamma$</td>
<td>$(6.0 \pm 0.8) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>957.78</td>
<td>$\rho\gamma$</td>
<td>$(29.1 \pm 0.5)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\omega\gamma$</td>
<td>$(2.75 \pm 0.23)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$2\gamma$</td>
<td>$(2.20 \pm 0.08)$ %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu^+\mu^-\gamma$</td>
<td>$(1.08 \pm 0.27) \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Meson $p_T$ spectra estimation

$$p_{T,\text{meson}} = \sqrt{p_{T,\text{pion}}^2 + M_{\text{meson}}^2 - M_{\text{pion}}^2}$$

\[ \frac{d\sigma}{p_T dp_T} = T(p_T)F_0 + (1 - T(p_T))F_1, \]
\[ T(p_T) = \frac{1}{1 + \exp \left\{ \frac{(p_T - \langle p_T \rangle)}{\sigma} \right\}}, \]
\[ F_0 = \frac{\exp \left\{ -ap_T - b(p_T)^2 + p_T/p_0 \right\}}{p_T}, \]
\[ F_1 = \frac{A}{p_T^n}. \]

Since it is difficult to measure mesons except for pion, the other mesons $p_T$ spectra are estimated by $m_T$ scaling from pion experimental data.

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Meson $v_n$ estimation

It is known that hadron $v_n$ as a function of $KE_T$ are scaled by the number of constituent quark. Meson $v_n$ is estimated from pion $v_n$.

$$p_{T,\text{meson}} = \sqrt{\left(\sqrt{p_{T,\pi}^2 + M_{\pi}^2} - M_{\pi} + M_{\text{meson}}\right)^2 - M_{\text{meson}}^2}$$
Hadronic decay photon $v_n$

Decay photon $v_n$ is simulated from meson input.

Systematic uncertainty
- Propagated from pion $p_T$ spectra
- Propagated from pion $v_n$
- Event plane determination
Direct photon $v_n$

\[ R_{\gamma} = \frac{N_{\text{inc.}}}{N_{\text{dec.}}} \]

\[ v_n^{\text{dir.}} = \frac{R_{\gamma} v_n^{\text{inc.}} - v_n^{\text{dec.}}}{R_{\gamma} - 1} \]

**Systematic uncertainty**
- Propagated from inclusive photon $v_n$
- Propagated from decay photon $v_n$
- Propagated from $R_{\gamma}$
- Event plane determination

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### Results & Discussion

#### Neutral pion $\nu_n$

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| Detector                      | $|\eta| <$ |
|-------------------------------|----------|
| Electromagnetic calorimeter (CNT) | 0.35     |
| Reaction Plane detector (Inner) | 1.5 - 2.8 |
| Reaction Plane detector (Outer) | 1.0 - 1.5 |
| MPC                           | 3.1 - 3.8 |
| BBC                           | 3.0 - 3.9 |
The event plane dependence of neutral pion $v_n$

Hadrons in high $p_T$ are originated from jet fragmentation.
- Study jet property

In peripheral event $v_2$ and $v_4$: positive
$v_3$: negative

In the $v_2$ case, there is the difference blue and red
Event plane dependence of $\pi^0 v_n$ in high $p_T$

Di-jet makes $v_{2,4} > 0$ and $v_3 \approx 0$.
Energy loss of path length dependence: $v_n > 0$
It can be understood in central event.

Negative $v_3$ and the difference of red and blue in $v_2$ are not understood.

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Jet effect in event plane determination

Event plane determination is much affected by jet effect in peripheral event due to small multiplicity. The trend is different in $v_2$ & $v_4$ and $v_3$ due to the initial geometry.

$v_2 & v_4 > 0 : v_3 < 0$

\[ \eta = - \ln \left\{ \tan \frac{\theta}{z} \right\} \]
a Multiphase transport model (AMPT)

event generator (HIJING) + parton cascade (ZPC) + hadronization + hadron cascade
P.R.C 72, 064901

3 M events including Jet > 20 GeV are analyzed.

Centrality is defined by the number of particles in $3.1 < |\eta| < 3.9$.

Pions are detected in $|\eta| < 0.35$.

Event Plane is measured in

1: $1.5 < |\eta| < 2.8$ (RxN(\text{In}))
2: $1.0 < |\eta| < 1.5$ (RxN(\text{Out}))
3: $1.0 < |\eta| < 2.8$ (RxN(\text{I+O}))
4: $3.1 < |\eta| < 3.8$ (MPC)
5: $3.1 < |\eta| < 3.9$ (BBC)
6: $1.0 < |\eta| < 1.5 + 3.1 < |\eta| < 3.9$ (RxN(In)+MPC)
Pion $v_n$ simulated by AMPT

Event plane dependence is found in $v_2$, it is similar to the experimental measurement. The $v_3$ shows similar trend less than 5 GeV/c.
Results & Discussion

Direct photon $\nu_n$
The results of neutral pion and direct photon $v_n$

- In low $p_T$ region
  Direct photon has non-zero and positive $v_2$ and $v_3$.
  The strength is comparable to the hadron $v_2$ and $v_3$.

- In high $p_T$ region
  Direct photon $v_n$ is close to zero.
Centrality dependence of $\gamma^{\text{dir.}}$ and $\pi^0$ in high $p_T$

$\gamma^{\text{dir.}}$ $v_2$ and $v_4 < \pi^0$ $v_2$ and $v_4$

$\gamma^{\text{dir.}}$ $v_3 \approx 0$

The direct photon $v_n$ is close to zero.
The difference between $\gamma^{\text{dir.}}$ and $\pi^0$ is understood that photon includes prompt photon which $v_n \approx 0$. 

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Blast wave model

Blast wave model is based on hydrodynamic model
Parameterizing the expanding medium at freeze-out temperature

\[ \frac{dN}{p_T dp_T} \propto \int d\phi I_0(\alpha_T)K_1(\beta_T) \]

azimuthal anisotropy:
\[ v_n(p_T) = \frac{\int d\phi \cos(n\phi) I_n(\alpha_T)K_1(\beta_T)\{1 + 2s_n \cos(n\phi)\}}{\int d\phi I_0(\alpha_T)K_1(\beta_T)\{1 + 2s_n \cos(n\phi)\}} \]

6 parameters
Freeze-out temperature: \( T_f \)
average velocity: \( \langle \rho \rangle \)
transverse anisotropy: \( \rho_2, \rho_3 \)
spatial anisotropy: \( s_2, s_3 \)
\[ \alpha_T(\phi) = (p_T/T_f) \sinh(\rho(\phi)) \]
\[ \beta_T(\phi) = (m_T/T_f) \cosh(\rho(\phi)) \]
\[ \rho(\phi) = \rho_0(1 + 2\rho_n \cos(n\phi)) \]
\[ \langle \rho \rangle = \frac{\int r(\rho_0 \times r/R_{max})dr}{\int r dr} \]

6 parameters are defined by hadron observables.
Photon spectra and \( v_n \) are predicted as massless particle (mass = 0).
Photon observables are well described with parameters defined from hadron. The $p_T$ spectra is described though temperature is very low ($T_{\text{eff.}} = 240$ MeV). It could be due to strong radial flow (like blue shift correction).
The probability of understanding photon puzzle

Blast wave model well describes photon $p_T$ spectra and $v_n$ at freeze-out temperature ($T_{FO} \approx 100$ MeV).
Effective temperature could be affected by strong radial flow.

The possibility that photons from early stage are not dominant.

Photon $p_T$ spectra and $v_n$ are calculated with blue shift effect.

\[
T' = T \sqrt{\frac{1 + \beta}{1 - \beta}}
\]

$T'$ : apparent temperature
$\beta$ : velocity of photon source
$T < T'$
Photon $p_T$ spectra and $v_n$ with blue shift effect

Assumption of photon source

- temperature decreases with the time: $T(t)$
- velocity increases with the time: $\beta(t)$
- azimuthal anisotropy increases with the time $v_n(p_T, t)$
- thermal photon momentum distribution:

$$n(p_T, t) = \frac{p_T}{\exp(p_T/T(t)) - 1}$$

$p_T$ spectra and $v_n$ at final state are calculated as:

$$n^{\text{fin.}}(p_T) = \int dt n(p_T, t)$$

$$v_n^{\text{fin.}}(p_T) = \frac{\int dt n(p_T, t)v_n(p_T, t)}{\int dt n(p_T, t)}$$

Effective temperature is taken via fitting by exponential equation to $p_T$ spectra.

The difference with experimental measurement is estimated as:

$$(V_{\text{obs.}} - V_{\text{cal.}})/E(\text{stat. } \oplus \text{ sys.})$$

$V_{\text{obs.}}$: experimental measurement

$V_{\text{cal.}}$: calculation

$E$: error of $V_{\text{obs.}}$
Basic assumption for yield, velocity, and anisotropy

The temperature is decreased from 300 MeV to 100 MeV. The time is defined by temperature.
Effective temperature with blue shift is higher than without correction. The $v_n$ are much underestimated.
Additional assumption

- **Yield dependence**
  
  Since photon source expands, the yield is assumed to get large with time.

  \[ N(t) = \int dp_T t^a n(p_T, t) \]

- **Velocity dependence**

  \[ \beta(t) = B \cdot t^b \]

- **Azimuthal anisotropy dependence**

  \[ \nu_n(p_T, t) = C(p_T) \cdot t^c \]
$p_T$ spectra and $v_n$ with relative yield dependence

$$N(t) = \int dp_T t^a n(p_T, t)$$

Photons from late stage:
low temperature & large $v_n$

The both of effective temperature and $v_n$ are affected.

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$p_T$ spectra and $v_n$ with velocity dependence

$$\beta(t) = B \cdot t^b$$

Effective temperature significantly decreases with increasing “b”.
The $v_n$ is a slightly affected.
$p_T$ spectra and $v_n$ with anisotropy dependence

$$v_n(p_T, t) = C(p_T) \cdot t^c$$

Since $p_T$ spectra is not affected, effective temperature is not varied.

The $v_n$ increases with "c" decreasing.
The differences ($\sigma T_{\text{eff}}$ and $\sigma v_2$) are varies uniquely with the parameters “a”, “b”, and “c”. They are selected so that $T_{\text{eff}}$ and $v_2$ are comparable to the experimental measurement.
**$p_T$ spectra and $v_n$ with selected parameters**

Parameter “b” is selected so that effective temperature is comparable to experimental measurement. The “c” is chosen to be comparable to $v_2$. 

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Selected dependence of velocity and $v_n$ could be studied. The time dependence of $v_n$ of medium shows that $v_n$ is saturated early.
Summary (1)

Neutral pion and direct photon $v_n$ are measured in $\sqrt{s_{\text{NN}}} = 200\text{GeV}$ Au+Au collisions at RHIC-PHENIX experiment.

Neutral pion $v_2$, $v_3$, and $v_4$ show different pattern in high $p_T$ region. In central collisions, hadron shows non-zero $v_n$.

- It could be understood that jet path-length dependence.
- In peripheral collisions, $v_2$ & $v_4$ have positive while $v_3$ shows negative.
- It could be due to jet effect on determining event plane.

Comparison of neutral pion and direct photon in high $p_T$ region. Hadron shows non-zero while photon $v_n$ is close to zero.
It could be understood that photon includes prompt photons with $v_n \approx 0$. 
Summary (2)

Strong radial flow effect could be the probability of explanation “photon puzzle”.
High effective temperature could be understood that photon emitted from the medium having large radial velocity at late stage.

Photon $p_T$ spectra and $v_n$ are calculated with blue shift effect.

The time dependences are selected so that effective temperature and $v_2$ are comparable to the experimental measurement. It is found that the medium azimuthal anisotropy is saturated early time of development.
Model comparison of photon $v_2$

Direct photon $v_2$
0-20 %
- Calorimeter
- Conversion
- Hess et al. (a)
- Hess et al. (b)
- Linnyk et al.

Private communication

20-40 %
- arXiv1403.7558 (a)
- arXiv1403.7558 (b)
- arXiv1404.3714

40-60 %

(Orange) Transport model considering photons from hadron phase
(Blue, red) Fireball model
Hydrodynamic calculations (cyan, pink, and violet) including photons from late state, are much underestimated.

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Model comparison of $v_2$ and $v_3$

Dark violet is based on magnetic field effect, upper limit is shown. Model calculations of photon $v_3$ are much smaller than experimental data.

The data of $v_3$ may help to constrain parameters in model calculations.

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External photon conversion method

Real photons from external photon conversion at the Hadron Blind Detector (HBD) readout plane are detected.

- Extend low $p_T$ limit

Consistent inclusive photon $v_n$ well

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External photon conversion method

1) real photon converts to $e^+e^-$ in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for photons
5) assume the same tracks originate in the HBD backplane
6) re-calculate momentum and pair mass with this “alternate tracking model”
7) for true converted photons $M_{\text{atm}}$ will be around zero

\[
\begin{array}{c}
M_{\text{HBD}}[\text{GeV}] \\
M_{\text{vtx}}[\text{GeV}]
\end{array}
\]
Thermal photons are predicted sensitive to $\eta/s$

Hydrodynamic calculation predicts that direct photon is sensitive to $\eta/s$ of QGP than hadron.
The ratio of $v_2$ to $v_3$ in $p_T$ region

- Photons don’t have strong centrality dependence at around 2-3 GeV/c
- Pions increase from central to peripheral

Photon and pion show different centrality dependence.

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Relative yield dependence

\[ N(t) = \int t^a n(p_T, t) \, dp_T \]

**Yield dependence**
- \(a=0\)
- \(a=1/4\)
- \(a=1/2\)
- \(a=1\)
- \(a=2\)
- \(a=4\)

\[ \beta(t) = B \, t \]

\[ v_n(p_T, t) = C(p_T) \, t \]

Relative probability density is modified.
The velocity dependence

The time dependence of velocity is modified.
The azimuthal anisotropy dependence

Azimuthal anisotropy dependence

$$N(t) = \int n(p, t) dp$$

$$\beta(t) = B t$$

$$v_n(p, t) = C(p_n) t^c$$

Temperature : $$T(t)$$

Velocity : $$\beta(t)$$

Azimuthal anisotropy : $$v_n(p, t)$$
Selecting $b$ and $c$

<table>
<thead>
<tr>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.86</td>
<td>0.02</td>
</tr>
<tr>
<td>1/4</td>
<td>1.98</td>
<td>0.03</td>
</tr>
<tr>
<td>1/2</td>
<td>1.77</td>
<td>0.04</td>
</tr>
<tr>
<td>1</td>
<td>1.47</td>
<td>0.06</td>
</tr>
<tr>
<td>2</td>
<td>1.04</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>0.63</td>
<td>0.14</td>
</tr>
</tbody>
</table>

$T_{\text{eff}}$ vs $a$ (left) and $v_2$ vs $c$ (right).
Medium effect ($R_{AA}$)

\[
R_{AA} = \frac{(1/N_{AA}^{\text{evt}}) d^2 N_{AA}/dp_T dy}{< N_{\text{coll}} >/\sigma_{pp}^{\text{inel}} \times d^2 \sigma_{pp}/dp_T dy}
\]

$R_{AA}=1$
not modified
$R_{AA}\neq 1$
medium effect

Hadron
less than unity
-> medium effect

**photon**

$R_{AA}=1$ : not modified
-> Emitted from initial hard scattering

$R_{AA}>>1$ : There are other photon sources which are not in p+p collisions.

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PreDefence (M.Sanshiro)
Event Plane resolution

\[
\langle \cos \{ n(\Psi_n^{\text{South}} - \Psi_n^{\text{North}}) \} \rangle = \sqrt{\langle \cos \{ n(\Psi_n^{\text{true}} - \Psi_n^{\text{obs.}}) \} \rangle} \\
\nu_n^{\text{true}} = \nu_n^{\text{obs.}} / \text{Res}(\Psi_n)
\]

Extracted from the correlation between the event plane angle measured by south and north.

The \( \nu_n \) measured with event plane should be corrected by the resolution.
The event plane dependence of direct photon $v_n$

$v_2$ vs $p_T$ for 0-20%, 20-40%, and 40-60%.

$v_3$ vs $p_T$ for 0-20%, 20-40%, and 40-60%.

$\gamma^{\text{dir.}} v_2$

$\gamma^{\text{dir.}} v_3$

Symbols:
- Blue dots: RxN(In)+MPC: $1.5 < |\eta| < 3.8$
- Red dots: RxN(Out): $1.0 < |\eta| < 1.5$

PreDefence (M.Sanshiro)
Charged hadron $v_n$

Non-zero positive $v_n$ are observed. The trend of centrality dependence is not similar.
Event Plane correlation

$\Psi_2$ and $\Psi_3$ are uncorrelated.

2015/1/23 PreDefence (M.Sanshiro)
Identified charged particle $v_n$

It is observed that all harmonics have mass ordering, there are meson and baryon splitting.
The number of constituent quark scaling (NCQ scale)

All particles are scaled by modified NCQ scaling.

(a) : \( v_2(KE_T)/n_q \)
(b) : \( v_n^{1/n} \) scaling
(a)+(b) : \( v_n(KE_T)/n_q^{n/2} \)

arXiv:1412:1038

2015/1/23 PreDefence (M.Sanshiro)
π^0 and γ^{dir.} \( v_2 \) measurement by STAR

\[ \gamma^{dir.} v_2 \text{ in high } E_T \text{ region are consistent with } 0 \text{ within systematic uncertainty, while } \pi^0 \text{ has positive } v_2. \]
photon $v_n$ measurement by ALICE

It is also observed that $\gamma^{\text{dir.}} v_2$ is positive in low $p_T$ at LHC-ALICE. $v_3$ measurement is ongoing.

2015/1/23 PreDefence (M.Sanshiro)
The comparison of charged pion and hydro-model

\( \pi^\pm : \text{arXiv:1412:1038} \)

Model : \text{arXiv:1403.7558}

Private communication

2015/1/23
The comparison of direct photon and hydro-model

0-20%

$V_2$

20-40%

$V_3$

$\pi^\pm$: arXiv:1412:1038

Model: arXiv:1403.7558

Private communication

2015/1/23

PreDefence (M.Sanshiro)
Comparison of neutral pion $v_2$ with previous results

They are consistent within systematic uncertainty.
Comparison of neutral pion $v_2$ with previous results

They are consistent within systematic uncertainty.
Comparison of inclusive photon $v_2$ with previous results

They are consistent within systematic uncertainty.
Comparison of neutral pion $v_2$ with charged pion $v_2$

They are consistent within systematic uncertainty.
Comparison of neutral pion $v_3$ with charged pion $v_3$

They are consistent within systematic uncertainty.
Comparison of neutral pion $v_3$ with charged pion $v_3$

They are consistent within systematic uncertainty.
Comparison of direct photon $v_2$ with previous results

They are consistent within systematic uncertainty.